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DYNAMICS OF WATER-MODERATED WATER-COOLED REACTORS AT ACCIDENTAL DROP OF COOLANT CIRCULATION

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1. INTRODUCTION

The correct selection of dynamic characteristics of a nuclear power plant will allow to provide its maximum reliability in the transient and accidental conditions.

One of the most essential branches in the dynamics of reactor systems of a water-moderated water-cooled type is the analysis of transient processes at a change of the coolant circulation in the primary circuit. In this event the following operating conditions of the power plant are of a great practical interest:

(a) the accidental drop of a coolant flow rate;

(b) the increase of a coolant flow rate at the pump starting.

The drop of a coolant flow rate may result in an unnecessary abrupt overheating of the fuel element cannings even after the chain reaction is ceased. Especially dangerous is melting of the fuel element canning due to the possibility of fission-product release into the circuit. Besides, at the canning temperatures somewhat higher than the melting point, the melting metal dangerously interacts with the water or steam generating a great amount of heat [1].

When starting the pump some sharp uncontrolled surges of neutron (and heat) power of the reactor may occur at a usually negative temperature coefficient of reactivity.

In this case the power increase is connected with the release of positive reactivity at a decrease of the bulk temperature of water in the reactor (the decrease of water temperature in the reactor is caused both by the increase of a coolant flow rate and by the possible delivery of some colder water from the starting pump pipeline to the reactor).

The designer's problem is to define the correlation between the characteristic parameters of a process leading to the predetermined transient conditions. The predetermined transient process may be characterized by a tolerable enthalpy of the coolant in the reactor and by the lack of heat exchange crisis (or by the maximum tolerable temperature of the fuel element canning).

Mathematically the problem is confined to a system of differential equations of common variable derivatives which are (partially) obtained by finding the mean values of equations in the partial derivatives:

(a) coolant flow equations;

(b) heat transfer equations;

(c) neutron dynamics equations;

(d) equations for external effects.

These equations with these or those suppositions are solved, as a rule, by means of computers. For the quick-operating part of the process may be used the method, accounting for the distribution of parameters (along the reactor height). The hydrolic part of the problem (the change of coolant circulation for one-phase liquid) is usually solved independently from the thermal one. The neutron dynamics at the intermittent insertion of large negative reactivities may be also separated from the thermal ones for the quick-operating part of the process.

For the purposes of preliminary designing, as well as for a better understanding of thermophysical and hydrodynamic processes proceeding in reactors, the analytical dependences are also useful which give the possibility to define in a general form the characteristic criterion of the process and approximately find the interconnection required for limiting the transient process within the tolerable limits of parameters changes.

Below, the main results of the study are outlined and some recommendations are given which should be followed, to our mind, during designing the reactors.

The more detailed data are supposed to be published later.

2. SYSTEM OF EQUATIONS FOR EXPRESSING CHANGE OF COOLANT CIRCULATION IN REACTOR CIRCUIT

The coolant flow equation can be easily obtained from the mechanics equation:

$$\frac{d}{dt}(mw) = \Sigma F \qquad (2.1)$$

and it has the following form:

$$\frac{\partial}{\partial t}\left(\frac{\gamma s w}{g}\right) + \frac{\partial}{\partial x}\left(\frac{\gamma s w^2}{g}\right) = F_1 \qquad (2.2)$$

Using the appropriate approximations for the forces of friction, pressure, gravity and local resistances acting in element dx of the circuit, from formula (2.2) it is possible to obtain the equation for time change of non-condensable coolant circulation in the closed circuit in the following form:

$$\psi\frac{dG}{dt} = \Delta P_{mov} - \Delta P_{res}, \qquad (2.3)$$

where:

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$$\psi = \frac{1}{g}\sum_j \frac{l_j}{S_j} \qquad (2.4)$$

(the summation is carried out by circuit sectors with mean parameters).

Adding the well-known equation for change of angular velocity of the pump rotor rotation to formula (2.3) we shall obtain the following system of equations:

$$\psi \frac{dG}{dt} = \Delta P_{mov} - \Delta P_{res} ;$$

$$I \frac{d\omega}{dt} = M_{mov} - M_{res} . \qquad (2.5)$$

It is convenient to write the system of equations (2.5) in a dimensionless form:

$$\tau_{hyd} \frac{d}{dt} \left(\frac{G}{G_o}\right) = \frac{\Delta P_{mov}}{\Delta P_o} - \frac{\Delta P_{res}}{\Delta P_o} ;$$

$$\tau_{mech} \frac{d}{dt} \left(\frac{\omega}{\omega_o}\right) = \frac{M_{mov}}{M_o} - \frac{M_{res}}{M_o} , \qquad (2.6)$$

where the values:

$$\tau_{hyd} = \frac{\psi G_o}{\Delta P_o} = \left(\frac{1}{g} \sum_i \frac{l_i}{S_i}\right) \frac{G_o}{\Delta P_o} \simeq \frac{2E_c}{N_c} ; \qquad (2.7)$$

$$\tau_{mech} = \frac{I\omega_o}{M_o} = \frac{I\omega_o^2}{N_p} = \frac{2E_p}{N_p} \qquad (2.8)$$

have the sense of characteristic time constants of the transient process.

Value τ_{hyd} (the hydrolic time constant of the coolant circulation change) characterizes a ratio of the kinetic energy accumulated by the coolant to the power required for overcoming the coolant flow resistance.

Value τ_{mech} (the mechanical time constant of a change of the rotor rotation angular velocity) characterizes a ratio of the kinetic energy accumulated in the pump rotating parts to the power in the pump engine shaft.

From equationg (2.2) a similar system of equations for the reactor with the branched primary circuit may be easily obtained. In particular, for a reactor with n loops in the i-th loop of which Pi pumps (provided for the simplicity with common coupling points) can operate in parallel, we shall obtain:

$$\psi_{ik} \frac{dG_{ik}}{dt} + \psi_i \frac{dG_i}{dt} + \psi_r \frac{dG_r}{dt} = \Delta P_{mov_{ik}} - [\Delta P_{res_{ik}} + \Delta P_{res_i} + \Delta P_r] ; \qquad (2.9)$$

$$I_{ik} \frac{d\omega_{ik}}{dt} = M_{mov_{ik}} - M_{res_{ik}} ;$$

$$G_i = \sum_{k=1}^{P_i} G_{ik} \ (k=1,2,\ldots P_i); \ G_r = \sum_{i=1}^{n} G_i \ (i=1,2,\ldots n).$$

Physically, the apparent conditions of the operating consistency of pumps in transient processes are as follows:

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(a) pressure equality in the transient process in common points of the fusion of different coolant flows;

(b) continuity of all the flow rates and angular velocities.

For illustrating purposes let us consider the condition of the operating consistency of pumps in the i-th loop, which is easily obtained from formula (2.9) and has the following form:

$$\Delta P_{mov_{ik}} - \Delta P_{res_{ik}} - \psi_{ik} \frac{dG_{ik}}{dt} = idem\,(t). \qquad (2.10)$$

After disconnecting of the ik-th pump, condition (2.10) is automatically maintained at the expense of the "kinetic force" flow $(\psi_{ik} \frac{dG_{ik}}{dt})$ rate till value G_{ik} has reached 0. When starting the pump, condition (2.10) may be satisfied only in case the started pump develops a certain pressure head. Up to this moment the pump may be considered to be operated in the non-delivery conditions. According to equation (2.10) the pump pressure head should not be less than a difference of the pressures in the inlet sector.

The conditions similar to condition (2.10) will take place for the joint operation of pumps in different loops as well.

It should be noted that if there is no flap in the pump, the reverse flow of the coolant through the stopped pump is possible. In this event the equations should be changed.

At last, it should be noted that after the pump is deenergized the interia of a jet can become an external force relative to the pump wheel. In this event, the pump will be under the hydroturbine operating conditions. It is obvious that it will take place in case the following equality is obtained:

$$\Delta P_{mov_{ik}} = 0 \qquad (2.11)$$

(in a general case, at $\omega_{ik} \neq 0$).

From this moment on the pump wheel is transferred from a motive force into a resistance; this concept should be put or taken into account in a system of equations, type (2.9).

Taking into account the considerations outlined above, the solution of the system of equations (2.9) may be provided by a computer.

The analytic solutions may be obtained by using a series of simplified suppositions. Below, these solutions are given for the case of interest for the circulating pumps.

3. CIRCULATING PUMP DEENERGIZING OR BREAKING

Under the term "pump deenergizing" we shall understand the deenergizing of feeders in case the pump is provided with an electric drive.

Using the well-known statistical dependences it is possible to approximately put down:

$$\Delta P_{mov} \simeq \frac{\Delta P_o}{1-\phi_o^2} \left[\left(\frac{\omega}{\omega_o}\right)^2 - \phi_o^2 \left(\frac{G}{G_o}\right)^2 \right], \qquad (3.1)$$

where value ϕ_o, expressing the pump transconductance can be obtained from the pump calculations and the experimental data.

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The circuit characteristics usually approach a square value of the flow rate, i.e.:

$$\Delta P_{res} \simeq \Delta P_o \cdot \left(\frac{G}{G_o}\right)^2. \qquad (3.2)$$

Moment of resistance in the pump is

$$M_{res} = M_{hyd} + M_{fr}, \qquad (3.3)$$

where:

$$M_{hyd} \simeq \frac{\Delta P \cdot G}{\gamma \omega \eta^o_{hyd} \cdot \eta^o_{vol}}; \qquad (3.4)$$

$$M_{fr} \simeq M^o_{fr} \cdot \left(\frac{\omega}{\omega_o}\right)^2. \qquad (3.5)$$

For analysis it is convenient to use also the following correlation:

$$M_{fr} \simeq M^o_{fr} \times \frac{\omega}{\omega_o} \cdot \frac{G}{G_o}, \qquad (3.6)$$

which gives the dependence within the range of $\frac{G}{G_o} \sim \frac{\omega}{\omega_o}$ quite near to expression (3.5) (value M_{fr} within the range of $\frac{G}{G_o} >> \frac{\omega}{\omega_o}$ is unimportant).

It is considered in the first approximation that from the moment of the pump deenergizing we have:

$$M_{mov} = 0. \qquad (3.7)$$

The effect of M_{mov} on the process will be evaluated separately.

The system of equations (2.6) together with the above-mentioned dependences will be written as follows:

$$\tau_{hyd}(1-\phi_o^2)\frac{dx}{dt} = y^2 - x^2; \qquad (3.8)$$

$$\tau_{mech}(1-\phi^2)\frac{dy}{dt} = -xy\left[1-\phi_o^2\left(\frac{M^o_{fr}}{M_o} + \frac{M^o_{hyd}}{M_o} \cdot \frac{x^2}{y^2}\right)\right],$$

where:

$$x = \frac{G}{G_o}; \qquad (3.9)$$

$$y = \frac{\omega}{\omega_o} \qquad (3.10)$$

From equations (3.8) we shall approximately obtain:

$$x \simeq \frac{1}{1+\frac{t}{\tau_{circ}}}, \qquad (3.11)$$

where:

$$\tau_{circ} = \tau_{hyd} + \tau_{mech} \qquad (3.12)$$

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Value $\tau_{circ.}$ (the time constant of coolant circulation drop) seems to be in the most simple case only a sum of the preliminary determined partial time constants.

When

$$N_c = N_p = N_{pas} \tag{3.13}$$

(that may take place in an ideal case, i.e. at $\eta_c = \eta_{vol} = 1$),

then:

$$\tau_{circ} = \frac{2(E_c + E_p)}{N_{pas}}, \tag{3.14}$$

i.e. value τ_{circ} expresses a ratio of the kinetic energy accumulated in the circuit (by the coolant and the pump) to the power for coolant pumping.

The greater the accuracy of expression (3.11), the better the correlation is satisfied:

$$\frac{\tau_{hyd}}{\tau_{mech}} + \frac{\tau_{mech}}{\tau_{hyd}} + 2 >> 1 - \phi_o^2. \tag{3.15}$$

Condition (3.15) is not rigorous. It may be shown that the solution for equations (3.8) within the range of $\tau_{hyd} \sim \tau_{mech}$ and $\phi_o = 0$, corresponding to the worst accuracy of approximation for equation (3.11), has the following form:

$$x = y\sqrt{1 - 2\ln y} \tag{3.16}$$

$$\frac{t}{\tau} = \sqrt{\frac{2}{e}} \cdot \int_{\frac{1}{\sqrt{2}}}^{\sqrt{\frac{1-2\ln y}{2}}} e^{h^2} dh$$

or, the solution for the nearest case is:

$$x = \frac{2\left(1 + 2\frac{t}{\tau}\right)}{\left(1 + 2\frac{t}{\tau}\right)^2 + 1}, \quad \tau = \tau_{mech} \quad \text{at} \quad \frac{\tau_{hyd}}{\tau_{mech}} = \frac{1}{2}; \tag{3.17}$$

$$y = \left[\frac{2}{\left(1 + 2\frac{t}{\tau}\right)^2 + 1}\right]^{\frac{\tau}{2\tau_{mech}}}, \quad \tau = \tau_{hyd} \quad \text{at} \quad \frac{\tau_{hyd}}{\tau_{mech}} = 2.$$

The comparison of dependences (3.11), (3.16), (3.17), made in dimentionless coordinates $(x, \frac{t}{\tau})$, shows that within the range of $\tau_{hyd} \sim \tau_{mech}$ expression (3.11) gives a considerable relative error, especially within the range of small flow rates. However, the absolute error which the designer is interested in does not exceed ~ 0.05 in x parts and this is quite suitable for practical calculations.

Using dependences (3.11) out of the system of equations (3.8) it is possible to obtain an expression for y, which allows to determine the moment of the pump transferring into the hydroturbine operating conditions. Below, the following limiting cases are of great interest:

(a) $\tau_{mech} >> \tau_{hyd}$.

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In this case (practically, independent of value ϕ_0) we shall obtain:

$$x \simeq y \simeq \frac{1}{1+\frac{t}{\tau_{mech}}}, \tag{3.18}$$

i.e., the process is determined by the interia of rotating parts of the pump. This is the range of proportionality between the pump rotor angular velocity variation and the coolant flow rate. In this case it is possible to employ relation x=y used by many authors (for example, See [2]). When employed in the system of type (2.9) this relation can considerably reduce calculations and in some cases will help to obtain approximate analytical dependences.

At $\tau_{mech} >> \tau_{hyd}$ it is desirable to determine the electromagnetic slowing-down of a rotor of the centrifugal pump with a closed-type asynchronous motor employed in high-pressure water-moderated water cooled reactors. After the high power pump is deenergized a slowing-down of its rotor occurs due to the interaction between the lowering rotating magnetic flux coupled with the rotor and the eddy currents induced by this flux in the pump stator material. Taking into account that the eddy current losses power (N_F) is proportional to the square of the number of full cycles of magnetic polarity reversal (in our case – to the square of the pump rotor angular velocity) and to the square of the greatest value of magnetic induction $(e^{-\frac{R_R t}{L_R}})^2$, it is possible to obtain the following expression:

$$x \simeq \frac{e^{\eta_F \frac{\tau_{el.mag}}{2\tau_{circ}} e^{-\frac{2t}{\tau_{el.mag}}}}}{e^{\eta_F \frac{\tau_{el.mag}}{2\tau_{circ}}} + \frac{\tau_{el.mag}}{2\tau_{circ}} \int_{\eta_F \frac{\tau_{el.mag}}{2\tau_{circ}} e^{\frac{-2t}{\tau_{el.mag}}}}^{\eta_F \frac{\tau_{el.mag}}{2\tau_{circ}}} \frac{e^{\xi}}{\xi} d\xi}, \tag{3.19}$$

where:

$$\eta_F = \frac{N_F}{N_p}. \tag{3.20}$$

$$\tau_{el.mag} = \frac{L_R}{R_R}. \tag{3.21}$$

(L_R and R_R – the inductance and the resistance of the rotor winding, correspondingly).
For the most practical cases value $\eta_F \frac{\tau_{el.mag}}{2\tau_{circ}} << 1$.

Having considered that in this case the main part of the intergrand is value $\frac{1}{\xi}$, we shall obtain from formula (3.19):

$$x \simeq \frac{1+\eta_F \frac{\tau_{el.mag}}{2\tau_{circ}} e^{\frac{-2t}{\tau_{el.mag}}}}{1+\frac{t}{\tau_{circ}} + \eta_F \frac{\tau_{el.mag}}{2\tau_{circ}}}. \tag{3.22}$$

Thus, a relative drop of the flow rate in transient operating conditions taking place due to the additional slowing-down of the rotor does not exceed, in this case, the value of $\eta_p \cdot \tau_{el.mag}/2\tau_{circ}$, that is usually not more than 0.07 in parts from x.

Expression (3.22) indicates that these effects decrease with an increase of value $\tau_{circ} \simeq \tau_{mech}$. At value $\tau_{mech} \simeq (2-3)$ sec. they may be neglected. Usually, value $\tau_{mech} \leqslant 1$ sec. Additional pump flywheel masses may considerably increase value τ_{mech}.

It should be noted that at $\tau_{mech} \gg \tau_{hyd}$ of the plant it is possible to approximately determine a relative drop of the flow rate in accordance with the experimentally measured change of the relative rotor angular velocity.

At $\tau_{mech} \gg \tau_{hyd}$ of the test bench it is possible to make measurements on an unnatural bench. It should be borne in mind that according to formula (2.8) for hot and cool systems there is the following approximate correlation: $\tau^{h}_{mech} \simeq \frac{\gamma_c}{\gamma_h} \cdot \tau^{co}_{mech}$ .... (3.23), i.e., a drop of the coolant flow rate in the hot circuit will be more gradual.

It is noteworthy that for the reactors with $\tau_{mech} \gg \tau_{hyd}$ a mechanical breaking or jamming of the pump rotor may be dangerous. In this case an accidental drop of the coolant flow rate may occur which is determined by low value τ_{hyd}. For these reactors it is desirable to have an emergency pump constantly connected (in parallel) to the circuit as a precaution measure.

(b) $\tau_{hyd} \gg \tau_{mech}$

In this case we shall obtain:

$$x \simeq \frac{1}{1+\frac{t}{\tau_{hyd}}} \quad ; \quad t \leqslant t_0 \tag{3.24}$$

(t_0 is the moment of pump transferring into the hydroturbine operating conditions). It may be shown that in this case value y tends rapidly to the following expression:

$$y \simeq \frac{\phi_0}{1+\frac{t}{\tau_{hyd}}} \quad ; \quad 0<\phi_0<1 \, , \tag{3.25}$$

i.e., according to formulae (2.11) and (3.1) the pump transfers into the hydroturbine operating conditions. It may be assumed with a margin that from the moment of pump deenergizing the following correlation takes place:

$$x \simeq \frac{1}{1+\frac{t}{\tau^{*}_{hyd}}} \quad , \tag{3.26}$$

where:

$$\tau^{*} = \frac{\tau_{hyd}}{1+\frac{\Delta P_{wheel}}{\Delta P_0}} \tag{3.27}$$

Value $\frac{\Delta P_{wheel}}{\Delta P_0}$ is of the order of 0.3 – 0.6 and may be obtained during the pump testing.

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(It should be noted that the employment of relation x=y for simplifying the calculations is physically not worth while in this case. But it cannot lead to an error if $\frac{\Delta P_{wheel}}{\Delta P_0} \ll 1$. It is explained by the fact that at $\tau_{hyd} \gg \tau_{mech}$ the contribution from the pump rotating parts is negligible and the approximation nature of value y for determining x is inessential).

In this case the experimantal determination of a drop of the coolant flow rate seems to be possible only in a real circuit. It should be noted that if tests are carried out in a cool circuit and the rating is self model then it may be considered that according to the equation (2.7):

$$\tau^{h}_{hyd} \approx \tau^{co}_{hyd} , \tag{3.28}$$

i.e., a drop the coolant flow rate will be almost the same both for the hot and cool systems.

The analysis of home big stationary reactor plants (for example, of the WWPR type) shows that the determining time constant for the considered process is value τ_{hyd}.

Qualitatively, it is possible to write:

$$\tau_{hyd} \simeq \frac{2}{w_0\left(\frac{\lambda}{d_{hyd}} + \frac{\Sigma\xi}{L}\right)} . \tag{3.29}$$

The average speed of coolant in the circuit (w_0) and the quantity of local resistances in the reactor per a length unit ($\Sigma\xi/L$) slightly change for various water-moderated water-cooled reactors.

In this case, usually

$$\frac{\lambda}{d_{hyd}} \gg \frac{\Sigma\xi}{L} .$$

Therefore, for the reactors with large hydrolic diameter (d_{hyd}) value τ_{hyd} is relatively great.

For the small-size reactors (for example, of the ice-breaker "LENIN" reactor type) the process is mainly determined by value τ_{mech}. The analysis of value τ_{mech} is difficult since dependence $I(N_p, \omega_0)$ is strictly constructive. When designing the pump it is expedient to put forward the requirement to have, if possible, value τ_{mech} great enough being $\gtrsim (1 \div 1.5)$ sec., which is possible to provide.

At last it should be noted that values τ_{hyd} and τ_{mech} are of the order of $(0.2 \div 1)$ sec. (The latter is obtained when the pump has no attached flywheel masses, for example due to the external pump engine for setting a low pressure).

4. TEMPERATURE PERFORMANCE OF REACTOR IN TRANSIENT CONDITIONS

Equations of the reactor thermal dynamics for slow processes or the processes comparable with the time of establishing the thermal equilibrium in a reactor may be obtained by reducing the corresponding equations in partial derivatives to the mean values.

In the most simple form they are reduced to regular balance equations, for example, of the following form:

$$C_u \frac{dT_u}{dt} = (q_0 F)\frac{n}{n_0} - (kF)_u (T_u - T_{can}); \tag{4.1}$$

$$C_{can}\frac{dT_{can}}{dt} = (kF)_u(T_u-T_{can.})-(kF)_{can}(T_{can}-T_c);$$

$$C_c\frac{dT_c}{dt} = (kF)_{can}(T_{can}-T_c)-GC_c^{sp}(T_{out}-T_{in}),$$

where:

$$T_c = \phi(T_{in}, T_{out}). \tag{4.2}$$

$$T_{in} = f(t) \tag{4.3}$$

and value T_c may be given proceeding from the physical considerations.

We shall not consider the equations of delay and heat exchange in communication lines and steam generators because for the most interesting quick part of the process in the given problem the operating conditions of reactor and steam generators are practically separated in time.

The system of type (4.1) together with the above-mentioned equations of type (2.9) for changing the coolant circulation and the known neutron dynamics equations give the possibility to express (in the point approximation) the transient behaviour of the reactor.

To find just the thermal time constants of the transient processes in the reactor, let us first consider transient thermal process when the emergency protection system is tripped at a constant flow rate of the coolant. This condition has much in common with the transient flow rate problem and is of particular interest. At a jump introduction of the great negative reactivity ($\rho_{em.prot} >> \beta$) by the emergency protection system, the temperature reactivity effects for the quick part of the process (i.e. at $T_{in} \simeq$ Const) may be neglected.

Then, at one group of delayed neutrons we shall approximately obtain:

$$\frac{\eta}{\eta_0} \simeq \frac{\beta}{\beta+\rho_{em.prot}} e^{-\frac{t}{\tau_{del}}} . \tag{4.4}$$

It can be shown that the effect of fuel elements canning on the character of transient processes in the water-moderated water-cooled reactor is small ($C_{can.} << C_u$; $C_{can} << C_c$). The value of canning heat capacity can be effectively considered in other constants (for example in C_u).

Then the system of equations (4.1) including formula (4.4) can be reduced to the following form:

$$\frac{\tau_{pas}}{2}\cdot\tau_u\frac{d^2\theta}{dt^2} + \left(\tau_u+\frac{\tau_{tr}}{2}\right)\frac{d\theta}{dt} + \theta = \mathrm{Const}\frac{\beta}{\beta+\rho_{em.prot}} e^{-\frac{t}{\tau_{del}}}, \tag{4.5}$$

where:

$$\theta=\theta_c = \frac{T_c-T_{in}^o}{T_c^o-T_{in}^o} \quad \text{at Const}=1; \tag{4.6}$$

$$\theta=\theta_{q_e} = \frac{T_u-T_c}{T_u^o-T_c^o} \quad \text{at Const}=1-\frac{\tau_{pas}}{2\tau_{del}}; \tag{4.7}$$

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$$\tau_u = \frac{C_u}{(kF)_u} = \frac{Q_u}{N_r} \tag{4.8}$$

$$\tau_{tr} = \frac{C_c + C_u}{G C_c^{sp}} = \frac{2a}{N_r} \quad . \tag{4.9}$$

$$\tau_{pas} = \frac{C_c}{G\, C_c^{sp}} = \frac{L}{W} \quad . \tag{4.10}$$

Value τ_u – the time constant of changing the fuel element (unit) temperature – characterizes a ratio of the excessive heat (as compared to the coolant heat) accumulated in the unit to the reactor power.

Value τ_{tr} – the transport or convection time constant of the reactor – characterizes a ratio of the heat generated by the fuel elements and coolant when they are cooled from the coolant average temperature to its temperature at the reactor inlet to the reactor power.

In the presence of the equation:

$$\tau_{tr} = \tau_{pas} \cdot \left(1 + \frac{C_u}{C_c}\right) \tag{4.11}$$

we may say that value τ_{tr} also characterizes the delay in the convectional heat transfer (along the reactor length) by the coolant due to the terminal heat capacity of the unit, i.e., it is the time for a heat pulse to expand in the reactor. It should be also noted that in the energy content of the reactor time constants considered here, value

$$\tau_r = \tau_u + \frac{\tau_{tr}}{2} = \frac{Q_{ac}}{N_r} \tag{4.12}$$

is the time constant of establishing the thermal equilibrium in the reactor and characterizes a ratio of the heat stored in the reactor to the reactor power.

Equation (4.5) may be easily solved.

We shall be interested in some limiting cases which are of a practical interest:

(a) $\tau_{tr} \gg \tau_u$. Then from equation (4.5) we shall approximately obtain

$(\tau_{del} \to \infty)$:

$$\theta_c \cong \frac{\beta}{\beta + \rho_{em.prot}} + \frac{\rho_{em.prot}}{\beta + \rho_{em.prot}}\, e^{-\frac{2t}{\tau_{tr}}} , \tag{4.13}$$

i.e., the transient process is determined by the time of heat wave expansion in the reactor. Physically, it means that the excessive heat in the fuel elements as compared to the coolant is neglected. In this case the fuel element temperature is close to the coolant temperature and it is possible to speak about cooling (heating) the reactor as a whole.

(b) $\tau_u \gg \tau_{tr}$.

In this case from equation (4.5) we shall obtain:

$$\theta_c \cong \theta_{q_e} = \frac{\beta}{\beta + \rho_{em.prot}} + \frac{\rho_{em.prot}}{\beta + \rho_{em.prot}}\, e^{-\frac{t}{\tau_u}} , \tag{4.14}$$

i.e., the transient process is determined by the thermal inertia of fuel elements, and a relative drop of the coolant temperature approximately coincides with a relative drop of the heat flow. Physically, it means that in this case the coolant heat capacity may be neglected.

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It follows from the examples considered above that the pump stoppage conditions are more dangerous for the reactor with the fuel elements of a high thermal potential, i.e., at $\tau_u >> \tau_{tr}$ (this, for example, occurs with the fuel elements made of sintered uranium dioxide).

It is possible to write, that:

$$\tau_u \simeq \frac{d_u^2}{\Lambda a_u} + \frac{C_u}{\alpha_g^{eff} \cdot F_u} + \frac{C_u}{\alpha_{can} F_u} + \frac{C_u}{\alpha_c F_u}, \tag{4.15}$$

where:

$$d_u = \frac{4F_u}{\Pi_u}. \tag{4.16}$$

(Λ – the coefficient of unit shape – may be obtained by solving the equation of heat conductivity in steady conditions).

For the medium size units using uranium dioxides (for example, for the ice-breaker "LENIN" reactors), the first two expressions for τ_u will be the main ones (due to the small heat-conductivity of uranium dioxide and the gas gap).

For the large size uranium dioxide units value is $\tau_u \sim \frac{d_u^2}{\Lambda a_u}$. Usually it is $\tau_u \sim (2 \div 5)$ sec. for the uranium dioxide fuel elements.

It is easy to show that when satisfying the condition:

$$\frac{\tau_{f.e}}{\tau_{circ}} \leqslant \frac{\rho_{em.prot}}{\beta + \rho_{em.prot}} \tag{4.17}$$

the coolant temperature in the reactor will not rise just after the pump deenergizing with a simultaneous triggering of the emergency protection system.

Here:

$$\tau_{f.e} = \frac{d_u^2}{\Lambda a_u} + \frac{C_u}{\alpha_g^{eff} F_u} + \frac{C_u}{\alpha_{can} F_u}. \tag{4.18}$$

Physically, condition (4.17) is quite simple, it requires that the initial drop of the heat flow should be more sharp than that of the coolant flow rate. For a deep drop of the power ($\rho_{em.prot} >> \beta$) condition (4.17) will be the following:

$$\tau_{f.e} \leqslant \tau_{circ}. \tag{4.19}$$

As mentioned above, value $\tau_{circ} \sim (1-1.5)$ sec. for the reactors where the pump is not provided with additional flywheels. Therefore condition (4.19) for the uranium dioxide units may be not completely satisfied, i.e., in this case a considerable rise of the coolant temperature is to be expected especially when there is delay between the signal arrival to the emergency protection system and the beginning of its efficient effect on the reactor power change ($\tau_{em.prot}$ equals some tenths of a second).

An approximate calculation of the parameters distribution (with respect to the reactor height) can be made in the following way.

Having accepted that in the heat exchange equation for the moving liquid

$$G\frac{\partial i_c}{\partial x} + \gamma S\frac{\partial i_c}{\partial t} = q_I \tag{4.20}$$

the variables in the expression for q_e are separated, it is possible to write its solution as follows.

(a) For the coolant particles being at the initial moment of transient process ($t=0$) inside the reacting core ($t_0' \leqslant 0$):

$$i_c(x,t) = i_{st}\left(x - \int_0^t w(t'')dt'';\ 0\right) + \int_{x-\int_0^t w(t'')dt''}^{x} q_l(x')\frac{N(t')}{N_0}\cdot\frac{dx'}{G(t')}\ , \tag{4.21}$$

where:

$$x' = x - \int_{t'}^{t} w(t'')dt'' \tag{4.22}$$

$$i_{st}\left(x - \int_0^t w(t'')dt'', 0\right) = \frac{1}{G_0}\cdot\int_0^{x-\int_0^t w(t'')dt''} q_l(x'')dx''\ . \tag{4.23}$$

(b) For the coolant particles being at the initial moment of transient process outside the reacting core ($t_0' \geqslant 0$):

$$i_c(x,t) = i_{in}(0, t_0') + \int_0^x q_l(x')\frac{N(t')}{N_0}\cdot\frac{dx'}{G(t')}\ . \tag{4.24}$$

(Moment t_0' of a coolant particle entry in the reacting core at the point of interest (x,t) is determined from expression (4.22) at $x'=0$).

The relative value of the heat flow transferred to the coolant

$$\frac{N}{N_0} = \frac{(kF)_{can.}(T_{can} - T_c)}{(kF)^o_{can}(T^o_{can} - T^o_c)} \tag{4.25}$$

can be obtained from the problem in point approximation.

It should be noted that for the fuel elements with a low heat potential ($\tau_u \ll \tau_{tr}$) the essential simplification of the problem is possible, namely: in dependences (4.21) — (4.24) it is adequate to supersede the coolant speed with the speed of heat wave expansion:

$$w_{tr} = w_0\frac{C_c}{C_c + C_u}\ . \tag{4.26}$$

In this case a relative drop of the neutron flow may be approximately used instead of the unknown heat flow.

In accordance with the plan considered above, this problem may be solved both in the point approximation and by calculating the parameters distribution. But these solutions are bulky. For preliminary estimations (marginly) the point model may be employed in its most rough form, assuming that:

$$i_{out} \simeq i_{in} + \frac{N}{G}\ . \tag{4.27}$$

It can be shown that for the elements with $\tau_u \gg \tau_{tr}$ for which the given problem is actual, a drop of the heat flow at a decrease of the coolant flow rate up to the flow rate of a small (steady) circulation practically coincides with that at the constant flow rate. It is connected with the fact that a drop of the heat flow due to the rise of the thermal resistance between the coolant and the unit is small in the given case.

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In view of the above-mentioned factors the connection of the process characteristic parameters can be easily obtained at which the relative temperature (or the enthalpy) of the coolant will not exceed the given value θ_{lim}, for example, in the following form:

$$e^{-\frac{\tau_{circ}}{\tau_u}} \; \frac{1-\varkappa}{\varkappa} \leqslant e^{-\frac{\tau_{em.prot}}{\tau_u}} \left[\left(1+\frac{\rho_{em.prot}}{\beta}\right)\varkappa\theta_{lim} - \frac{1}{\rho_{em.prot}/\beta}\right], \tag{4.28}$$

where:

$$\varkappa = \frac{G_{st}}{G_o} \tag{4.29}$$

$$\theta_{lim} = \frac{i_{lim} - i^o_{in}}{i^o_{out} - i^o_{in}} \; . \tag{4.30}$$

Value θ_{lim} is apparently to be taken from the no-boiling condition of the coolant in the reactor.

Value $\rho_{em.prot}/\beta$ taken from the temperature effect overlapping condition at the reactor cooling up to value $\sim T^o_{in}$ is from 2 to 4. In this range it does not limit the process considered. The effect of $\rho_{em.prot}/\beta$ decreases with the increase of value τ_u because in this case the process is determined to a greater extent by the excessive heat of the fuel elements and not by the internal heat release.

For the fuel elements with $\tau_u \ll \tau_{tr}$ practically there is no problem of emergency heat removal after stoppage of the pumps.

In this case condition (4.17) for the absence of the coolant temperature surge is satisfied. For the reactors of this type there are mainly two moments:

(a) Value $\tau_{em.prot}$.

With some margin it may be considered that for limiting the coolant temperature overrising by value θ_{lim} for time $\sim\tau_{em.prot}$ (at approximately rated power of the reactor) it is necessary that:

$$\frac{\tau_{em.prot}}{\tau_{circ}} < \theta_{lim} - 1 \; . \tag{4.31}$$

For the intensive power water-moderated water-cooled reactors value θ_{lim}, taken from the no-boiling conditions of the coolant, is equal to 2–3 and condition (4.31) may be easily satisfied (if there is no breaking in the pump).

It should be also noted that it is desirable to have:

$$\tau_{em.prot} \lessdot \tau_{pas} \; . \tag{4.32}$$

In this case the integral of the heat accumulated by a coolant particle for time $\sim\tau_{em.prot}$ will be small.

(b) To provide the given value θ_{lim} in the process end it is necessary (marginly) that:

$$\varkappa\theta_{lim} \geqslant \frac{\beta}{\beta+\rho_{em.prot}} \; . \tag{4.33}$$

At last the approximation of type (4.27) is noted to be essentially improved by selecting the physically approved effective centre of heat removal in the reactor and to be reduced, for example, to the following form:

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$$i_{out}(t) \simeq i_{in}\left(t - \frac{\tau_{pas}(t)}{2}\right) + \frac{N\left(t - \frac{\tau_{pas}(t)}{2}\right)}{G\left(t - \frac{\tau_{pas}(t)}{2}\right)} . \qquad (4.34)$$

The expression of type (4.34) may give the close coincidence with the problem of distributed parameters (along the reactor height).

5. HEAT EXCHANGE CRISIS IN REACTOR IN TRANSIENT PROCESS

Using the approximate static dependences for determining the critical heat loads it is possible to evaluate the margin on a heat exchange crisis in the transient conditions. For example, using (at a constant pressure) the dependence presented in [3]:

$$q_{cr} = \mathrm{Const}\,(w\gamma)^{\frac{1}{2}} \times (T_s - T_c)^{\frac{1}{3}} \qquad (5.1)$$

it can be shown that for the considered problem the margin on the critical load in the transient process will immediately decrease, if:

$$\frac{\tau_u}{\tau_{circ}} \gtrsim 2\,\frac{\rho_{em.\,prot}}{\beta + \rho_{em.\,prot}} . \qquad (5.2)$$

In this case the value of small (steady) circulation can determine only the minimum to which this margin will drop.

It follows from this that when satisfying correlation (5.2), it should be given that:

$$n_{q_{cr}}(x, o) = \frac{1}{K_{trans}} \geqslant 1. \qquad (5.3)$$

i.e. it is necessary to have a dynamic margin already in the stable operating conditions. It should be noted that the transition into boiling conditions will require the further increase of this margin.

From the previously given data it is also clear that correlation (5.2) will, for example, take place for the fuel elements made of uranium dioxide. The transient conditions may be preliminarily estimated (marginly) in the point approximation.

Let us assume that:

(a) Position of the dangerous point in the reactor (x_{dan}) is not changed in the transient conditions.

(b) Minimum margin on the critical load ($n_{q\,cr}$) occurs at the moment of transition entry into the stable (small) circulation.

(These assumptions correlate quite well with more accurate calculations including the parameters distribution along the reactor). In this case, formula (5.1) including, the following parameters correlation may be obtained which does not result in (marginly) the heat exchange crisis in the transient conditions connected with stoppage of the pumps and operation of the emergency protection system:

$$\varkappa \leqslant \frac{\left[1-\frac{\theta_{lim}-1}{\theta_s(x_{dan})-1}\right]^{\frac{2}{3}}}{\theta_{lim}^2 \times K_{trans}^2} \tag{5.4}$$

where:

$$\theta_s(x_{dan}) = \frac{T_s - T_{in}^o}{T_c^o(x_{dan}) - T_{in}^o}, \tag{5.5}$$

value $\varkappa$ in expression (5.4) being taken from equation (4.28). To determine q_{cr} the dependences of type (5.4) can be obtained with approximations different from equation (5.1). If estimations should be made frequently, dependences (4.28) and (5.4) may be shown graphically in the form of nomograms.

If the condition of type (5.4) in not satisfied, the heat exchange crisis may occur in spite of the chain reaction cessation. In this case the high heat load in the reactor is very specific because it results from the high temperature potential of the fuel elements. At the first moments after a steam blanket is formed on the unit surface, the temperatures are equalized along the core section and the element canning. The further cooling (heating) of the unit as a whole depends on the correlation between the fuel element temperature drive, its internal heat release and the heat removal after the heat exchange crisis.

An approximate analytical solution of the problem may be obtained from the equation system of type (4.1) on the assumption that the coolant temperature is constant while at the moment of heat exchange crisis the heat-removal coefficient with regard to the coolant discontinuously changes up to some constant value α_c^{bl}.

Then for the most dangerous case ($C_{can} \ll C_u$) from the point of view of the unit melting, we shall obtain for not too small values of t:

$$\theta_{can} \simeq \frac{\eta_{int}^*}{\eta_{\theta I}} \left[1-\left(1-\theta_u^* \frac{\eta_{cr}}{\eta_{int}^*}\right) e^{-\frac{t}{\tau_u^{bl}}}\right] \tag{5.6}$$

where:

$$\theta_{can} = \frac{T_{can} - T_c^o}{T_{can}^o - T_c^o} \tag{5.7}$$

$$\theta_u^* = \frac{T_u^* - T_{can}^*}{T_u^o - T_{can}^o} = \frac{T_u^* - T_c^o}{T_{can}^o - T_c^o} \cdot \frac{\tau_2}{\tau_1 + \tau_2^*} \tag{5.8}$$

$$\tau_1 = \frac{d_u^2}{A a_u} + \frac{C_u}{\alpha_g^{eff} \cdot F_u} + \frac{C_u}{2\alpha_{can} \cdot F_u}; \quad \tau_2 = \frac{C_u}{2 d_{can} \cdot F_u} + \frac{C_u}{d_c \cdot F_u} \tag{5.9; 5.10}$$

$$\tau_2^{\theta I} = \frac{C_u}{2\alpha_{can} F_u} + \frac{C_u}{\alpha_c^{\theta I} F_u} \tag{5.11}$$

$$\tau_u^{\theta I} = \tau_1 + \tau_2^{\theta I} \tag{5.12}$$

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$$n_{int}^* = \frac{\beta}{\beta + \rho_{em.prot}} e^{-\frac{t^*}{\tau_{del}}}$$

$$n_{\theta I} = \frac{r_2}{r_2^{\theta I}} \cdot \qquad (5.13)$$

$$n_{cr} = \frac{r_1 + r_2^{*}}{r_1 + r_2^{\theta I}} \qquad (5.14)$$

(* is true for the time moment just preceeding the heat exchange crisis).

From equation (5.6) we shall obtain that the initial surge of value θ_{can} gives the following value:

$$\theta_{can}(o) \simeq \theta_u^{*} \frac{r_2^{bl}(r_1 + r_2^{*})}{r_2(r_1 + r_2^{bl})} \cdot \qquad (5.15)$$

At the complete cessation of heat removal $(r_2^{bl} \to \infty)$ from equation (5.15) we shall obtain:

$$\theta_{can}(o) \simeq \theta_u^{*} \frac{r_1 + r_2^{*}}{r_2} = \frac{T_u^{*} - T_c}{T_{can}^{o} - T_c} \quad , \qquad (5.16)$$

which means that $T_{can} \simeq T_u^{*}$, i.e., at the period of temperature equalization along the unit the canning temperature will not exceed the average core temperature occurred at the moment of heat exchange crisis; physically, this is quite obvious.

A further behaviour of T_{can} is determined, as it is seen from equation (5.6) by the relation:

$$\theta_u^{*} \frac{n_{cr}}{n_{int}^{*}} \gtrless 1 \; , \qquad (5.17)$$

For example, to lower the canning temperature after a short surge for the most dangerous (theoretically) case – the heat exchange crisis at the moment of scram system triggering it is necessary that:

$$n_{cr} > \frac{\beta}{\beta + \rho_{em.\,prot}} \qquad (5.18)$$

The analysis of real values of α_c^{bl} shows that for the elements with $r_u \gg r_{fr}$ (for example, elements made of uranium dioxide) condition (5.18) may be satisfied. It means that canning temperature in the transient conditions does not exceed (marginly) the average core temperature occurred in the rating. Therefore, if

$$T_{can}^{melt} \gtrsim T_u^{o} \; , \qquad (5.19)$$

then, the melting of canning for the fuel elements of this type may not occur. Condition (5.19), as a rule, is satisfied on the uranium dioxide fuel elemets for the high-melting materials of the canning (steel, zirconium alloy) at high enough heat loads. For the fuel elements of this type with the aluminium alloy lower heat loads are essential.

If $r_1 \ll r_2$ then, after the temperatures equalization along the unit, a further increase of value T_{can} is possible. In this case it is necessary that:

$$\theta_{can}^{melt} > \frac{n_{int}^{*}}{n_{bl}} \cdot \qquad (5.20)$$

The similar conditions should have place for the core temperature of the fuel element as well.

Thus, in case of the heat exchange crisis on subcooling water the conditions may occur which do not lead to melting of the fuel element canning or core.

The detailed analysis when designing the reactor may help to determine the permissible limits of short-time operation of the reactor within the range of increased temperatures of the fuel elements.

MAIN SYMBOLS

G – weight flow rate of coolant
ω – angular velocity of rotation
I – moment of inertia
M – moment of rotation
m – mass
ΔP – pressure drop
N – power
E – kinetic energy
Q – heat ammount
W – coolant speed
S – passage cross-section for coolant
F – heat exchange surface
d – diameter
Π – perimeter
l,L – length
ξ – local resistance coefficient
η – efficiency
n – neutron flux
ρ – reactivity
β – delayed-neutron fraction
i – enthalpy
T – temperature
C – heat capacity
γ – specific gravity
α – heat-removal coefficient
k – heat-transfer coefficient
a – thermal diffusivity
q – heat flow
g – gravity acceleration
e – 2.71828 ...... constant
τ – time constant
t – time

INDICES:

mov – moving
mech – mechanical
vol – volume
fr – friction
c – coolant
p – pump
el.mag – electromagnetic
l,L – refers to length term
st – steady
s – saturation
u – unit
F – Foucault
can – canning
in – inlet
out – outlet
cr – crisis
bl – blanket
int – internal
g – gap
melt – melting
pas – passage
lim – limiting
del – delay
circ – circulation
f.e – fuel element
h – hot
co – cold
pum – pumping
em. prot – emergency protection
sp – specific
ac – accumulated
eff – effective
trans – transient
dan – dangerous
rat – initial conditions (rating)
r – reactor
res – resistance
hyd – hydraulic

REFERENCES

1. *L.F.Epstein,* Journal of Nuclear Energy, Part B, V.3, 1962
2. *D.I.Blokhintzev, M.E.Minashin, U.A.Sergeev.* "Atomnaya Energiya", No.1, 1956.
3. *B.A.Zenkevich, V.I.Subbotin.* "Atomnaya Energiya", No.8, 1957.
4. *C.M.Boyd, J.r., R.M.Posser, B.B.Gardwell, J.r.,* Nuclear Science and Engineering, V.9, No.4, 1961.
5. *K.Pfleiderer. Mashgiz, M.,* 1961.
6. *B.V.Kitaev, I.F.Grevtzev.* Sudpromizdat, 1960.

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